CINEMATOGRAPHIC STUDY OF SOLID PROPELLANT COMBUSTION IN AN ACCELERATION FIELD

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THESIS

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April 1970

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by

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ABSTRACT

The influence of an acceleration field on the combustion rate of a composite solid propellant when directed normally and into the burning surface was recorded by high speed cinematography.

One-half to one-inch long propellant strands with 1/4-in by 1/4-in cross sections were burned and photographed at pressures of 200 psi and 500 psi while subjected to normal acceleration fields of 0 g and 75 g.

Aluminized propellants were primarily utilized in this investigation; however, the experimental apparatus and the techniques used proved suitable for general propellant studies.

Propellants burning in acceleration fields of 0 g and 75 g were successfully filmed at frame rates of 4500 pictures per second. The designed magnification factor and the quality of the motion pictures produced provided an optical definition of particle sizes to 100 microns. This film resolution allowed an optical analysis of the acceleration effects on propellant burning rates.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

Grateful acknowledgement is given to Professor David Netzer, Mr. Paul Willoughby of the United Technology Center, and Mr. Edward Michelson for their respective talents and contributions without which this effort could not have been successfully completed.

I. INTRODUCTION

A composite solid propellant subjected to an acceleration field normal and into the burning surface experiences a change in the burning rate observed under unaccelerated conditions [1,2,3].

Past investigations [1,4,5] have shown that for both metallized and nonmetallized propellants the augmented burning rate:

(a) decreases with increasing base burning rate.

(b) increases with acceleration directed normally and into the burning surface.

An increase in the burning rate augmentation as pressure is increased has also been observed for the propellants in these investigations, but it is not a universal trend.

In addition, for the metallized propellants, the augmented burning rate has been observed to:

(a) increase with increasing aluminum particle size [1,6].

(b) decrease as the ammonium perchlorate crystal size is reduced.

The results of these past investigations show that the burning rate of both metallized and nonmetallized propellants are acceleration sensitive.

The primary objective of this experimental investigation was to cinematographically record and observe the burning surface of metallized and nonmetallized propellants subjected to an acceleration force directed normally and into the burning surface.

II. EXPERIMENTAL APPARATUS

The equipment[1] used in this investigation, shown in Figure 1, was located at the Naval Postgraduate School's Rocket Laboratory.

The centrifuge is electrically driven by a one-hp motor through a variable speed hydraulic transmission, producing a maximum of 800 g at 1800 RPM. For purposes of this investigation the table speed was set at 475 RPM, which generated a normal acceleration field of 75 g. A slip ring assembly consisting of 4 pairs of 5 amp and 4 pairs of .5 amp leads was installed in the centrifuge shaft providing electrical power at the rotating table surface.

The Centrifuge table, shown in Figure 2, supports the following major components of the experimental equipment.

Combustion Bomb

The combustion bomb, shown in Figure 3, was constructed from 2024T351 aluminum to withstand an internal pressure of 2000 psi. Three plexiglass windows are installed in the combustion bomb. Two windows, located diametrically opposite, are separately utilized for cinematographic

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[1] All major components of the system were designed by investigators at the United Technology Center [3].

observation of the propellant strand. A General Electric Marc 300/16 projection lamp, and a solenoid operated lamp shutter are mounted above the third window to illuminate the propellant strand during filming. A similar bomb installed directly opposite the combustion bomb was connected by 3/8-in stainless steel tubing, and acted as a pressure ballast and counterbalance.

A Continental Screw Type blowout disc assembly was installed in each bomb. A pressure transducer was mounted on the main combustion bomb.

Pressurization and Purge System

Nitrogen was supplied from four high pressure lecture bottles to pressurize and purge the combustion bomb. A zero to 2500 psi pressure regulator was installed in the system to maintain a pre-selected bomb pressure. A high pressure solenoid valve was mounted upstream from the pressure regulator.

Photographic-Optic System

Two mirrors and a Pentax Auto-Takumar 3:5, 135 mm lens, were used to project the propellant strand image to a Hycam, model K1001, 16 mm high speed motion picture camera mounted in a stationary position above the rotating table, as shown in Figures 2 and 4. The Hycam, model K1001, has a frame rate capability from 100 to 8500 pictures per second and is controlled by the input voltage. The additional illumination necessary to photograph at high frame rates was supplied by a General Electric Marc 300/16 projection lamp mounted in a dichoric reflector. An infrared filter was located between the lamp and the illumination window to filter out all but the visible light spectrum. A solenoid operated shutter was also installed over the illumination window. The shutter was opened just prior to ignition to prevent inadvertent propellant ignition or excessive heating by the lamp radiation. The Hycam camera was used with an extension tube adapted to a 50 mm lens which provided approximately a 1.5 magnification factor.

Electrical Systems

The Control Panel was designed to allow remote control of all system components. The lamp, shutter, and purge events were manually programmed and initiated. The order of the sequence, ignition camera or camera ignition, could be pre-selected. An Agastat pneumatic adjustable time delay relay was installed between the ignition and camera circuits. Selection of the first event automatically initiated the second. A Delco 12 V DC reversible motor with an internal brake was used to provide remote control for the variable speed hydraulic transmission. An RPM gauge was mounted on the control panel, recording twice table RPM.

Photographic Materials

The Hycam, model K1001, camera utilizes 100 foot rolls of 16 mm film. Kodak Ektachrome EF 7241 Daylight film with an exposure rating of 160 was used for all color cinematography. This is a high speed color reversal film for use under low level illumination or for high speed photography. The developed film is suitable for direct projection with the capability of color print reproduction.

Black and white results were obtained with use of Kodak Double X DXN 449 Negative film with an exposure rating of 250. Standard black and white photographs can be developed directly from this film.

Standard commercial techniques were employed for developing and printing all films.

III. EXPERIMENTAL PROCEDURES

Propellant strands used in this experiment were prepared one-quarter inch by one-quarter inch in cross section and cut in one-half and one-inch lengths. A solution of methylmethacrylate and acetone, and a kerpco heat resistant spray paint were employed separately as inhibitors and were applied to all surfaces of the propellant strand except the normal burning surface.

The propellant sample was then bonded with cement to an aluminum pedestal and mounted in the end cap of the combustion bomb as shown in Figure 5. An ignitor, consisting of a composition of black powder and cement, was applied to the propellant ignition surface. Burning was initiated by use of a nichrome resistance ignition wire placed in contact with the ignitor.

Both the combustion bomb and ballast bomb were equipped with a blowout disc assembly. The burst-disc installed in the ballast bomb was designed to rupture at 461 psi.

The combustion and ballast bombs were initially pressurized to 370 psi to prevent a rapid nitrogen depletion in the nitrogen supply bottles once the purge sequence was activated.

The burst-disc located in the combustion bomb was designed to rupture at 760 psi and functioned only as a safety valve to prevent overpressurization of the bomb. An orifice installed upstream from the disc assembly in the ballast bomb regulated the nitrogen flow volume once the disc had burst.

The output of a pressure transducer mounted on the combustion bomb was connected to a Visacorder oscillograph giving a time history of the bomb pressure.

Once the entire system had been pressurized to 370 psi, a solenoid operated high pressure valve was closed. This isolated all components from the nitrogen supply bottles. These high pressure bottles were then charged to a pressure of 1800 psi. The supply bottles are capable of providing a constant combustion bomb pressure of 500 psi for 5.85 seconds. A pressure of 500 psi was maintained in the combustion bomb during burning. This pressure was controlled by a dome-loaded high pressure regulator mounted on the rotating table surface as shown in Figure 2. The dome assembly was initially charged with nitrogen to 500 psi. The pressure regulator then reduced the 1800 psi supply to provide a constant outlet pressure of 500 psi to the vented combustion bomb.

This nitrogen flow pressurized the combustion bomb to the desired level and provided a system purge. The purge flow rate past the propellant sample in the bomb was approximately 2 ft/sec. The main purpose of this nitrogen flow rate was to prevent smoke accumulation in the optical path. This flow also assisted in inhibiting erosive burning on the propellant sides.

Camera shutter speeds approaching the maximum for a given light intensity were attempted. The camera framing rate was directly controlled by the input AC voltage. The camera was equipped with a standard 1/2.5 shutter[1] which produced a shutter speed per frame equal to 1/2.5 times 1/frame rate.

The light intensity produced from the propellant burning surface and projection lamp determined the maximum frame rate used for each propellant investigated. For the non-aluminized propellant, the aperture was initially set fully open.

Suitable aperture settings for the aluminized propellant which burned with a greater light intensity were determined from experiment.

A timing light was mounted in the camera optical head assembly which could be used to produce a mark on the film every 1/120 of a second when powered by standard 110V AC

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1 The Hycam camera uses a selectable rotary shutter to provide a variable range of shutter speeds for a given camera framing rate.

power. This provided a method for calculating the actual frame rate at each individual frame during analysis.

Experimental runs were conducted under two acceleration conditions, 0 g and 75 g. For all runs at 75 g the rotating table was first accelerated to the desired RPM.

The projection lamp, if required, was turned on and given 45 seconds to obtain maximum intensity. The purge sequence was then initiated by opening the high pressure valve and supplying the 1800 psi nitrogen to the regulator. The regulator in turn provided a 500 psi outlet pressure which initially builds the pressure in the combustion and ballast bomb from 360 psi to the burst disc pressure of 461 psi. Following disc rupture the pressure continues to rise during venting to 500 psi and remains constant until nitrogen depletion occurs. The pressure build-up (measured on the Visacorder) occured within 0.15 sec. Immediately following the burst-disc rupture, the lamp shutter was opened and ignition initiated. The augmented burning rates for the propellants investigated were used in estimating the total strand burning times [4].

Sample strands of propellant were mounted on the end cap and ignited openly to determine the delay in ignition. In all tests propellant ignition occured within 0.2 sec.

The filming time available at the particular camera speed selected was used to determine the necessary time delay in camera actuation. This allowed filming the burning propellant at a fixed focal field centered 0.15 in from the bottom of the strand, while the camera was operating at full speed. This computed delay time was then set on an adjustable time-delay relay which automatically initiated the camera following ignition.

Camera filming times for 100 foot rolls varied from 0.74 sec at 8000 pictures per sec to 4.7 sec at 1000 pictures per sec.

IV. PROPELLANTS

The composition of the propellants used in this investigation and the designations given to them are summarized in Table I. All propellants used were fabricated at the Naval Weapons Center, China Lake. The American Potash and Chemical Corporation was the supplier for all ammonium perchlorate used. The aluminum in the metallized propellants N6 and N7 was type H-30, and passed a tyler #325 mesh.

VI. EXPERIMENTAL RESULTS

General

The propellants and experimental conditions for all runs are summarized in Table II. The experimental conditions are classified in two general categories; the initial investigation at a pressure of 500 psi, and a second series of tests conducted at 200 psi.

Series 1

The camera field of view with the one-inch long strand mounted on the end cap was set to cover the bottom 0.65

inches of the propellant strand, with the critical focal point situated 0.15 inches from the bottom and 0.07 inches in from the corner, as shown in Figure 6. Although the propellant was within the camera field of view during 65% of burning it was in sharp focus only during its transit through the position 0.15 inches above its base. With the camera mounted in a staionary position above the rotating table, the image of the propellant produced on the film rotated. Every effort was expended in the optical alignment to insure that the focal point was the center of rotation. Any deviation from this arrangement produced an eccentric motion on the film and moved the focal point slightly in and out of center view and focus. The magnification factor for the first series of runs was approximately 0.90.

The camera framing rate for the first run was set at 2000 pictures per second (pps), with the lens fully opened at an aperture setting of 1.9 (fl. 9), to experimentally determine the correct aperture stop for filming propellant N1 at 1/5000 sec shutter speed. The propellant was cut 1 inch in length and inhibited on all sides with three coats of Kerpco high temperature paint.

Camera sequencing was set with a one-second delay, which afforded the propellant enough time to burn into the field of view and the camera to accelerate to full framing speed. As the propellant burned through the critical focal area, .15 inches from the base, the camera was operating at the full framing rate.

The results of Run 1 established an initial criterion for filming speed and aperture stop for the N1 propellant. It was determined that enough light was available to successfully film the burning surface at camera framing rates approaching 6000 pps. The paint inhibitor used was found to be unacceptable due to a delayed separation of the residue, which masked viewing the propellant burning edge. Focus was found to be extremely critical and restrictive within the field of view, as had been anticipated.

Propellant N6 was burned on the second run with the camera set for a framing rate of 4000 pps at f8.0. An increase in the light intensity produced on the propellant burning surface due to aluminum content allowed a higher frame rate and aperture stop. The results of these first two runs established the capability of filming at framing rates approaching 6000 pps for both the aluminized and non-aluminized propellant.

On runs number 3 through 8, propellants N2 and N7 were photographed at a framing rate of 3000 pps. Film of the N1 propellant burning at zero g indicated that the ammonium perchlorate (AP) crystal size of 9 microns was too small to allow significant optical evaluation. The 90 micron AP crystal size of propellants N2 and N7 provided a greater probability of detailed surface observation.

The results of the first series of runs were evaluated primarily on the procedural techniques and cinematographic quality. The films produced from this first series of runs indicated the necessity for a framing rate greater than 3000 pps. Burning particles on the propellant surface were moving too rapidly to achieve an adequate focus and definition. Movement of the flame pattern on adjacent frames was also erratic and poorly defined.

Focusing at a predetermined point on the propellant was found to be severely critical. Although a great portion of the propellant sample was within the field of view throughout the filming process, the camera was in critical focus at one location, the center of image rotation.[1] Pre-focusing on this point was accomplished using a dummy propellant with a point target measuring 0.005 in.

There was some eccentric motion involved with the rotation of the image, which resulted in the target area passing slightly in and out of focus. Efforts to align the optical equipment to insure centered rotation were difficult and time consuming, due to the restricted field of view associated with extension-tube magnification.

The flame pattern at a pressure of 500 psi was extremely dense for both propellants. This flame masked the propellant burning surface and prohibited any surface particle observation, except at the extreme edges of the propellant. The burning pressure was consequently reduced to 200 psi in an attempt to overcome this restriction.

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1 The camera being stationary above the rotating table causes apparent image rotation on the film.

In the initial tests, magnification was considered adequate for an overall observation; however, for the purpose of observing individual particle burning, an increase in magnification was required.

Subsequent to this first set of runs the propellant overall length dimension was changed to 0.50 inches to facilitate the sequence timing, and to provide a higher probability of filming success in the event of erratic or erosive burning.

Series II

For the second series of runs, pressure in the combustion bomb was reduced from 500 psi to 200 psi. The magnification factor was increased to 1.5 by increasing the length of the extension tube an additional 1 and 5/8 in. This increase in magnification reduced the camera field of view to an area 0.28 inches by 0.23 inches centered at a point 0.15 in from the base of the propellant. The slight eccentric rotation encountered in the first series of runs was eliminated, which gave a pure rotation about the focal point.

Focusing ability was greatly improved through the use of a ground glass focusing gate and 5-power eye piece. The focus point, as shown in Figure 6, remained the same on both series of runs.

The camera framing rate was increased to 4500 pps, which approached the maximum attainable, even though higher camera framing rates are advertised. Severe film damage resulted in attempts to achieve higher frame rates. Runs number 11 through 14 were conducted with propellant N7 under conditions shown in Table II. The films produced the desired focal acuity necessary for adequately observing the burning surface in detail.

Focus, although pre-set at a point within the propellant, as shown in Figure 6, was acute throughout the first one-quarter of the burning surface. This provided an enlarged area within which the burning phenomena could be adequately observed. The 4500 pps framing rate reduced particle velocity substantially, permitting a frame analysis of the individual burning particles.

VI. CINEMATOGRAPHIC ANALYSIS

The high speed color film produced in this experimental investigation was examined with a Kodak Analyst Model BP-16AR stop-action projector.

The primary objective of this investigation was to obtain the capability of viewing the propellant surface, in order to observe the influence that an acceleration field produced on propellant combustion.

The remarks that follow in the remainder of this section were derived from the general and detailed observations of all film produced.

Propellant N7 at 0 g

The aluminum particles were observed to ignite on the burning surface. Rapidly thereafter the burning particles were ejected from the propellant surface. The burning particles assumed a spherical shape while on the surface and continued to burn in the flame after leaving the surface. The primary force exerted on the burning particle is the drag force experienced in the gaseous stream. The burning aluminum particles did not noticably coalesce on the surface but appeared instead to be single particles undergoing ignition and combustion. The particle sizes were uniform and left the surface immediately after ignition. There appeared to be no agglomeration of ejected aluminum particles once they entered the gaseous stream.

Figure 7 is a frame series photograph, taken at 0 g, of the aluminum particles leaving the propellant surface. The two large particles approximately 200 microns in diameter were observed leaving the surface in close proximity. The sizes of the remaining particles in this sequence are representative of the 0 g burning observations.

The sequence of frames in Figure 7 shows that the two larger particles do not coalesce. The aluminum particles were ejected off the burning surface soon after ignition. The 4500 pps framing rate was inadequate in producing a clear photograph of the mean size particles, indicating a relatively high velocity. The larger particles in Figure 7 moved with a lower velocity and are more clearly defined. A detailed examination of the movie film showed that the propellant burning surface was uniformly receding and only slightly irregular in the vicinity of an ejected aluminum particle.

Propellant N7 at 75 g

The same N7 propellant, burned under conditions of 75 g and 200 psi, produced a notable change in the burning mechanism both on and off the propellant surface. Figure 8 clearly shows an aluminum particle initially igniting while within the relatively dark propellant surface. In the remaining two frames the particle begins to burn with a brighter intensity and leaves the surface. The larger the aluminum particle appeared, the longer it remained on the surface. Figure 9 presents two separate frame sequences which show the agglomeration observed on the surface during acceleration runs. The frame sequence for the left photograph is from top to bottom. The two aluminum particles located on the right hand corner coalesce in the last frame.

The photograph on the right is a similar example of agglomeration. The sequence of frames for this photograph is from bottom to top.[1]

In the first frame two large brightly burning particles are coalescing while two smaller ones on each side have just ignited on the surface. The smaller particles only appear to grow in size as the burning becomes brighter. As the frame sequence continues, the two adjacent particles coalesce with the larger particle. In both series of frame sequences the particles do not leave the burning surface.

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[1] The film strip was oriented with the propellant surface on the bottom for ease of photographic interpretation.

At this point in the burning sequence the acceleration force must be greater than the drag forces exerted on the spherical bodies. The force driving the particles (situated in close proximity) together may be the result of a pressure imbalance created on these spherical bodies in a velocity field. One other noticable observation is the resulting pit formation as the particle continues to burn on the surface. The aluminum particle agglomeration is again shown in Figure 10.[1] The left sequence of frames shows two larger agglomerates on the propellant surface coalescing to one.

The right sequence involves three larger aluminum particles which can be observed joining to one while still on the surface. Print 2 in the right series of Figure 10 allows a reasonable observation of the surface texture. The luminosity of the burning particles permits observation of the pit formation on the surface. In this instance the pits appear to be of the same magnitude as the burning particles.

This traverse motion and agglomeration of the aluminum particles on the propellant surface was observed on all acceleration runs. If the agglomerate grew by coalescence faster than combustion decreased its size, the particle

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[1] Photographs in Figure 10 were obtained by photographing the 16 mm projected image with a 35 mm camera, developing and enlarging. Prints in Figure 9 were obtained by producing a contact negative and then contact printing the negative. Both procedures appear adequate; however, the latter is preferred.

remained on the surface. Figure 11 is an example of such a massive agglomeration which formed. Two large particles on the order of 3000 microns can be seen in the photograph. In both instances large pit formation has accompanied the agglomeration. In many instances on the film, the particle pit formation was so severe the burning particle disappeared from view. The pit formed by the burning agglomerate helped sustain its existence on the surface. New aluminum particles which appeared and ignited on the walls of the formed pit were forced towards the bottom by the acceleration vector, where the smaller particles coalesced and continued to burn with the larger agglomerate.

In a few observed cases of pit formation near the propellant edge, the larger particle eventually burned through the side and spilled into the purging nitrogen flow. The acceleration force then propelled the particle upstream. Aluminum particles initially igniting on this spillway were immediately forced off the surface by the acceleration.

Reference 3 reported similar occurrences, and defined the amount and degree of agglomeration in stages. Stage one agglomeration occurs soon after ignition, with the formation of a large number of smaller coalesced aluminum particles. Stage two is reached when these particles begin to form distinct pits on the burning surface. As these pits increase in diameter they eventually merge. Stage three agglomeration occurs when the large globule can no longer maintain its spherical shape. Stages four and five are reached as this globule becomes increasingly oblate, eventually covering the entire surface with AL/AL_2O_3 slag. Figure 11 is an example of stage two pit formation. The aluminum slag particle basically retains a spherical shape and continues to burn in a stable manner within the formed pit. In the film, from which this frame was taken, the pit growth proceeded to stage three. The spherical shape became unstable, periodically distorting, and moved about in the pit. Further transformation to defined stages four and five where the aluminum slag begins to cover the entire surface was not observed. This phenomenon would be difficult to observe because of the initial restrictive surface area of the propellant strand and the degree of aluminum slag spillage observed in earlier stages.

The irregular shape of the propellant in Figure 10 is attributed to nonuniform ignition. Although there is the appearance of a residue breaking primarily from the propellant sides, this is most likely the propellant binder which has been consumed at a slower rate than the ammonium perchlorate crystals.

VII. CONCLUSIONS

The primary cause of the burning rate augmentation experienced with an aluminized propellant, in an acceleration field directed normally and into the burning surface, is the aluminum agglomeration.

The greatest change observed in the films taken at 0 g and 75 g was the increased aluminum particle size and agglomeration which occurred at the higher acceleration level. The aluminum agglomeration appears to be a function of the acceleration level, the aluminum particle size cast in the propellant, and the burn time (strand length).

The acceleration level of 75 g prevented the ignited aluminum particles from being immediately ejected from the burning surface. The aluminum particles burning on and in the proximity of the surface initially moved at random, probably as a result of pressure imbalances in the velocity field. These particles either burned until the acceleration and drag forces became equal, at which time they left the surface, or they collided with one another, effectively increasing the mass and size of the particle. As the burning progressed, smaller aluminum particles igniting on the surface were forced into coalescing with the larger particles. The larger particles held on the surface burned into the surface at a rate greater than the rate at which adjacent surface burned, forming a pit. This larger particle, or agglomerate, was continually fed by smaller particles both igniting below it and emerging from the pit walls. Continued burning resulted in greater pit depth and agglomerate size. The sperical shape of the particle eventually started distorting as the external forces, acceleration and unbalanced pressure from the velocity field, overcame the surface tension force. Depletion burn-out of the propellant occurred at this stage of agglomeration.

The increase in burning rate observed in the pits leads to the conclusion that the degree of augmentation is a function of the pit density, which in turn is dependent upon the number and size of the agglomerates. This in turn is directly related to the acceleration level and burn time.

The propellant thickness, or strand length in this instance, is also important in considering the size and number of agglomerates formed. The 1/2-in length propellant strands used in this investigation only approached the stage 3 agglomeration, as shown in Figure 11, when subjected to 75 g. It can be assumed that a higher acceleration level for the same 1/2-in strand length, or a longer strand at 75 g, would produce an agglomeration of stage 4 or higher.

One factor not previously noted or mentioned in investigating this augmentation is the smaller aluminum agglomerates which momentarily are suspended in the flame pattern off the surface until the drag force predominates. The nearness and density of these particles radiate an additional energy to the surface. This phenomenon is minor to the surface agglomeration, but noteworthy.

REFERENCES

1. Sturm, E. J., "A Study of the Burning Rates of Composite Solid Propellants in Acceleration Fields," Ph.D. Thesis, Naval Postgraduate School, Monterey, March 1968.

2. Northam, G. B. and Lucy, M. H., "On the Effects of Acceleration Upon Solid Rocket Performance," paper presented at ICRPG/AIAA 3rd Solid Propulsion Conference, Atlantic City, New Jersey, 4-6 June, 1968. AIAA Paper No. 68-530.

3. National Aeronautics and Space Administration CR-66824, "Photographic Study of Solid Propellants Burning in an Acceleration Environment," by P. G. Willoughby, K. L. Baker and R. W. Hermsen, September, 1969.

4. Naval Postgraduate School Report NPS-57 NT 9101A, "An Investigation of the Effects of Acceleration on the Burning Rates of Solid Propellants," by D. W. Netzer, R. C. Bates, W. Bringhurst, Jr., M. J. Bulman, 1 October, 1969.

5. Northam, G. B., "Effects of Steady State Acceleration on Combustion Characteristics of an Aluminized Composite Solid Propellant,: NASA TN D-4914, December, 1968.

6. Willoughby, P. G., Crowe, C. T., Dunlap, R., and Baker, L. G., "Investigation of Internal Ballistic Effects in Spinning Solid Propellant Motors, "UTC Report No. UTC 2281-FR, October 1968, Final Report on NOSC Contract No. N00017-67-C-2429.

TABLE I

Composite Propellant Formulations

Propellant	%AP Weight	AP Size(μ)	%PBAN* Weight	%AL Weight	AL Size(μ)
N1	79	9	21		
N2	79	90	21		
N6	67	9	18	15	44
N 7	67	90	18	15	44

*Polybutadiene-Acrylic Acid-Acrylonitrile

TABLE II

Experimental Run Conditions

Run No.	Propellant	Acceleration	Camera Speed	Aperture
Series I	500 psi	One Inch Strand Length		
1	N1	0 g	2000	1.9
2	N6	0 g	4000	8.0
3	N2	0 g	3000	2.8
4	N7	0 g	3000	16.0
5	N2	75 g	3000	2.8
6	N7	0 g	3000	8.0
7	N2	75 g	3000	4.0
8	N7	75 g	3000	5.6
9	N7	0 g	3000	5.6*
10	N2	0 g	3000	5.6*
Series II	200 psi	One Half Inch Strand Length		
11	N7	75 g	4500	5.6
12	N7	75 g	4500	4.0
13	N7	75 g	4500	4.0
14	N7	0 g	4500	4.0

* Black and White Negative Film

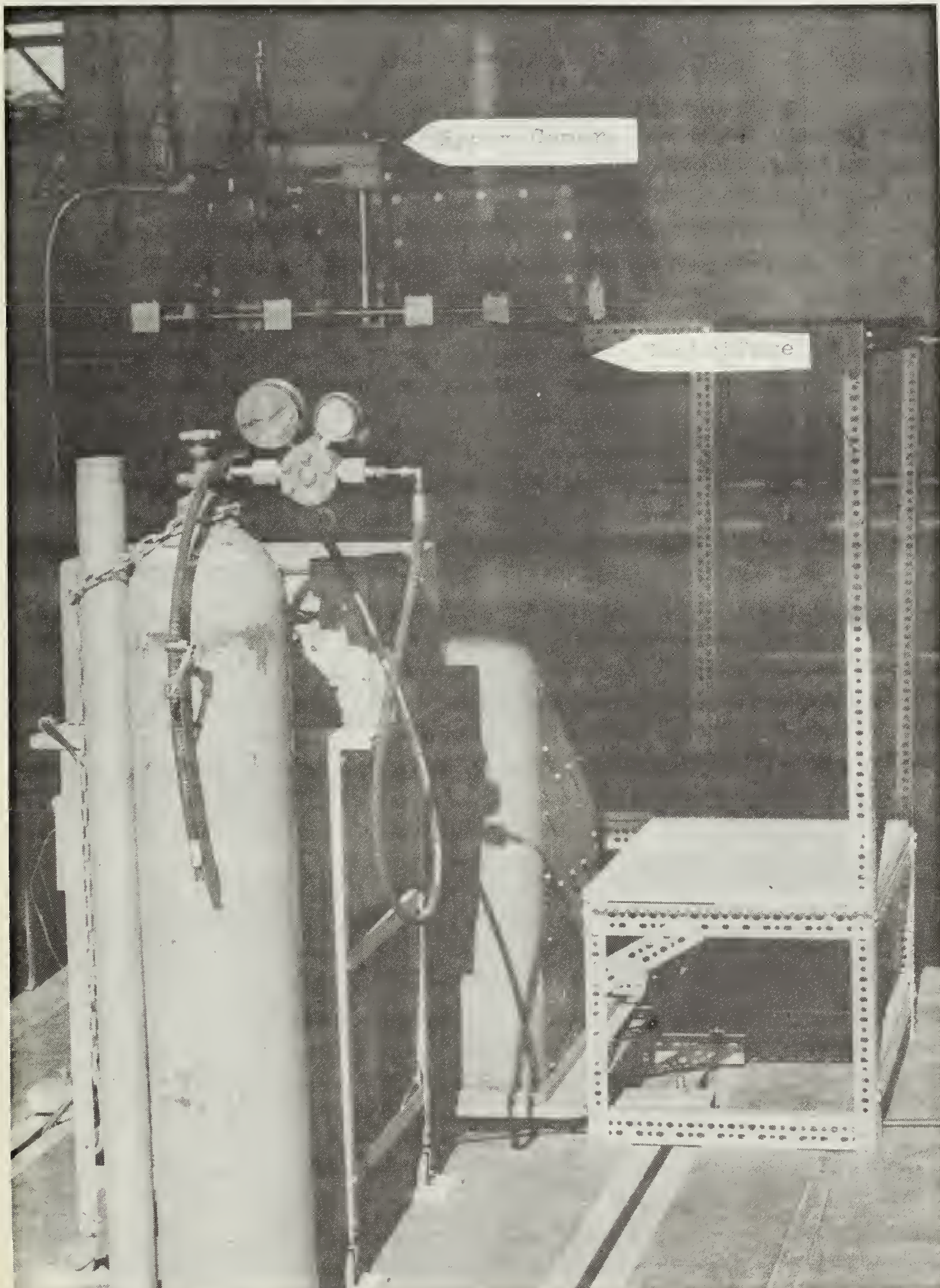


Figure 1. Optical Centrifuge

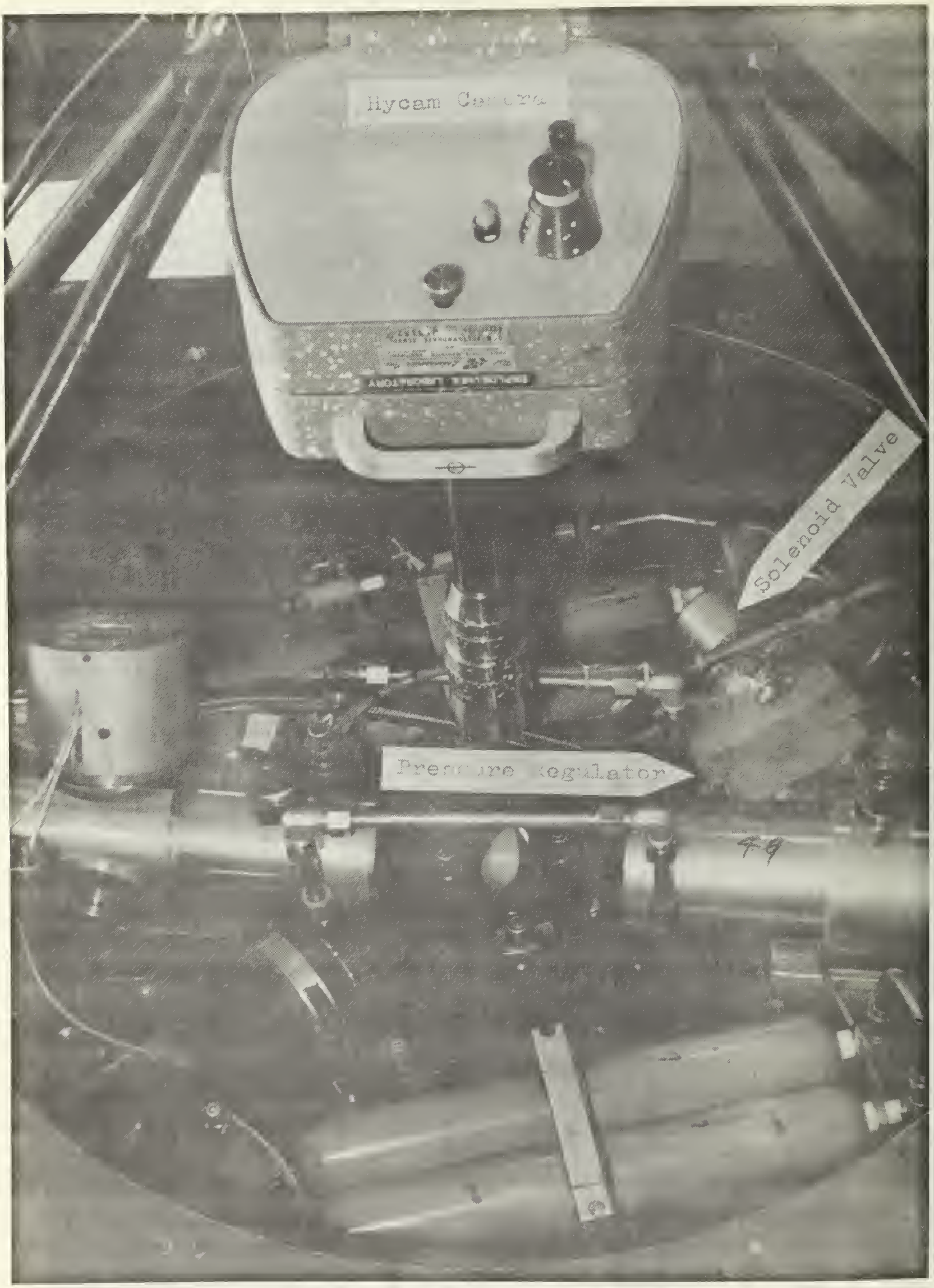


Figure 2. Centrifuge Table, Top View

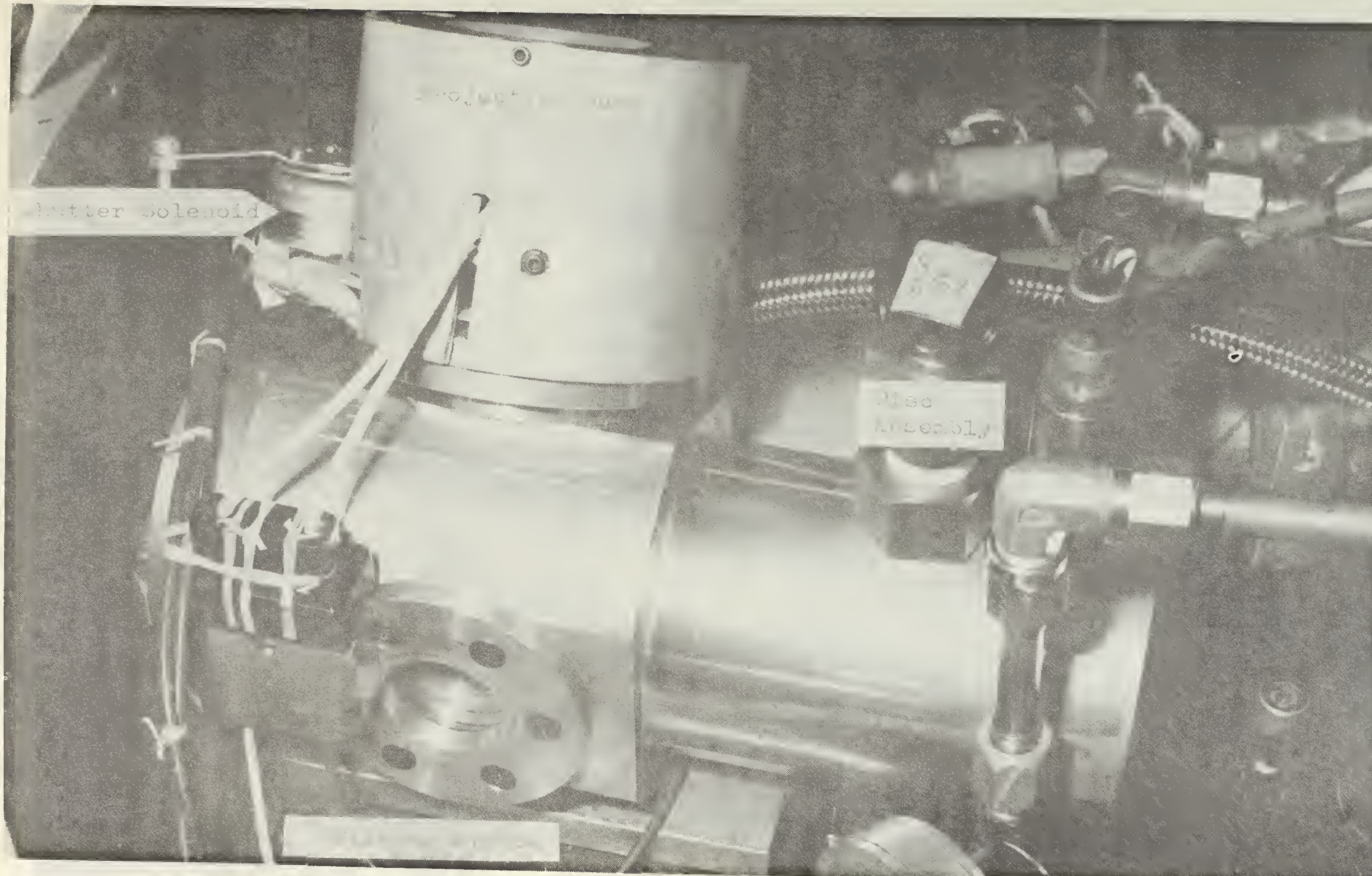


Figure 3. Combustion Bomb

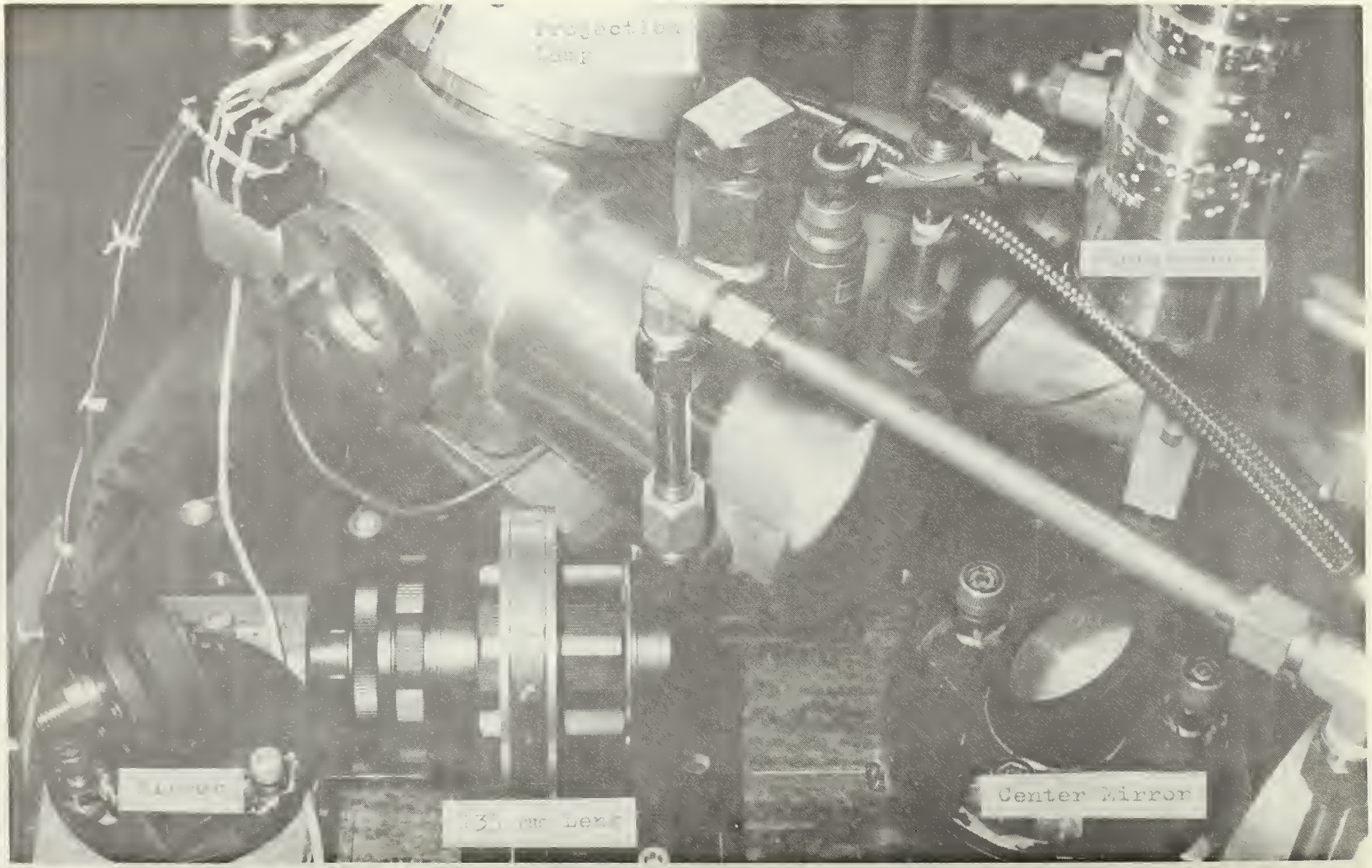


Figure 4. Camera Optics Arrangement

Figure 5. Combustion Bomb End Cap with Propellant Strand

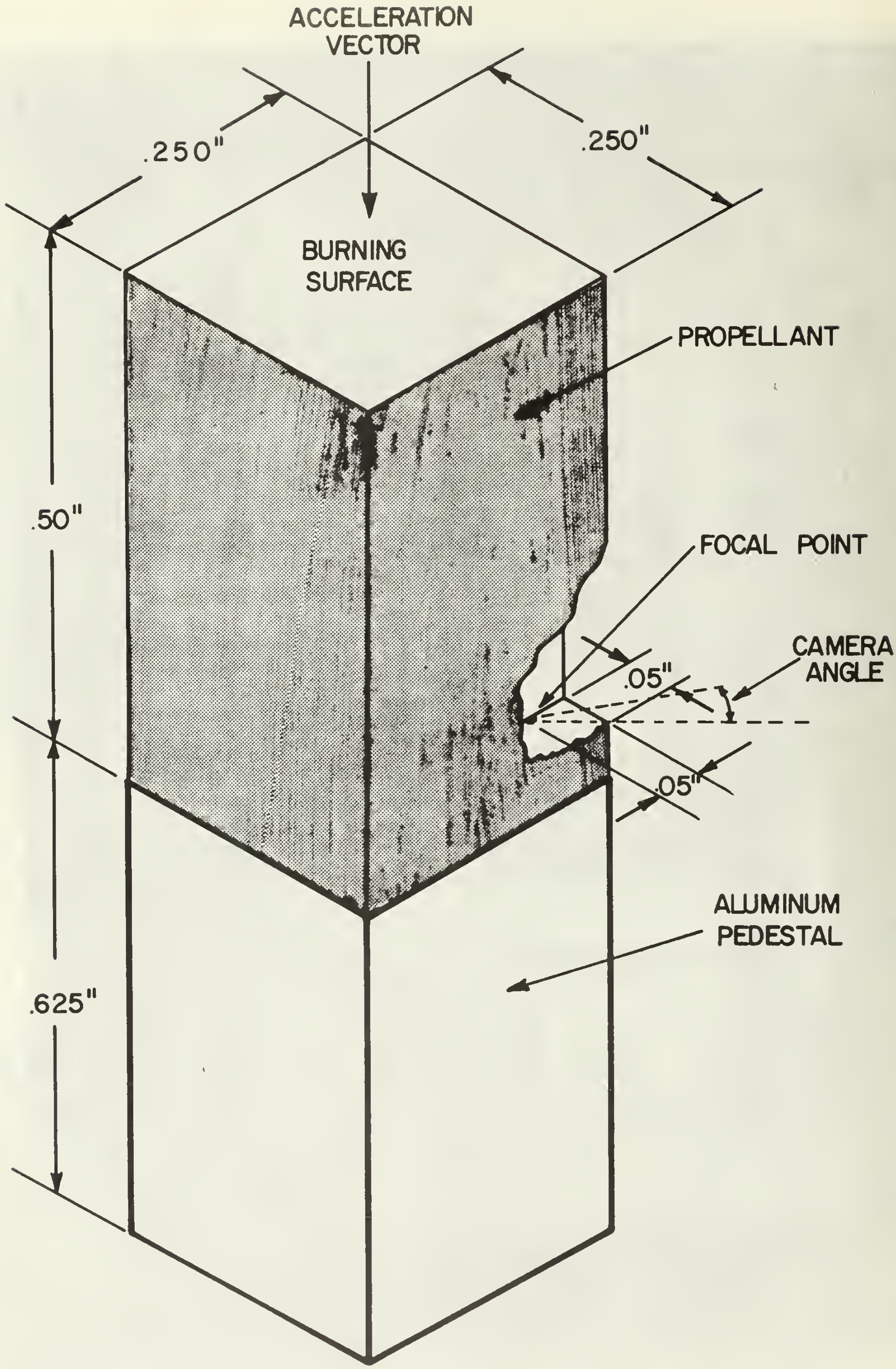
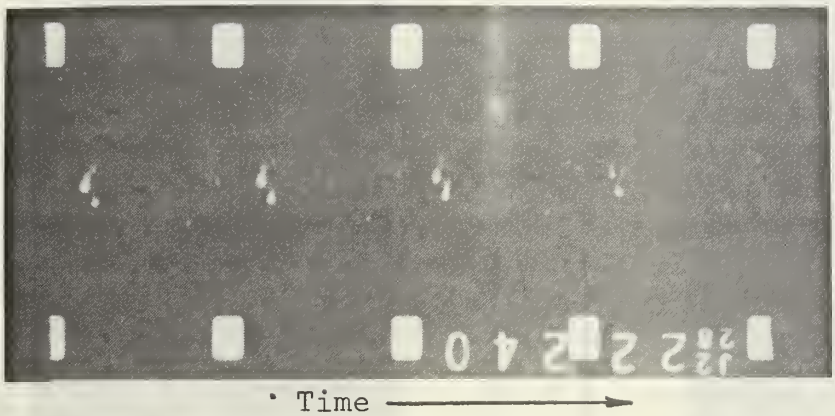
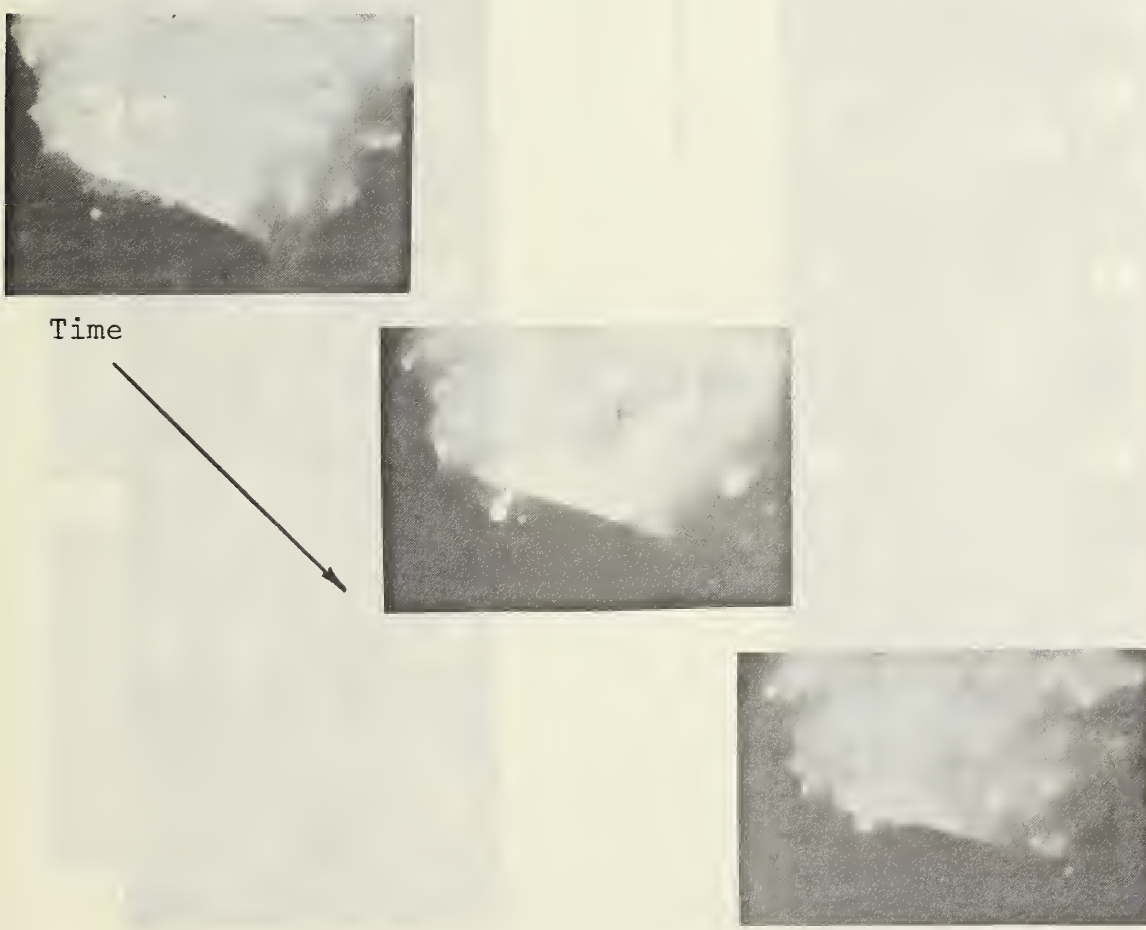


FIGURE 6. PROPELLANT STRAND DIMENSIONS



·Figure 7. Aluminum Particle Ejection, 0 g



·Figure 8. Aluminum Particle Ignition, 75 g

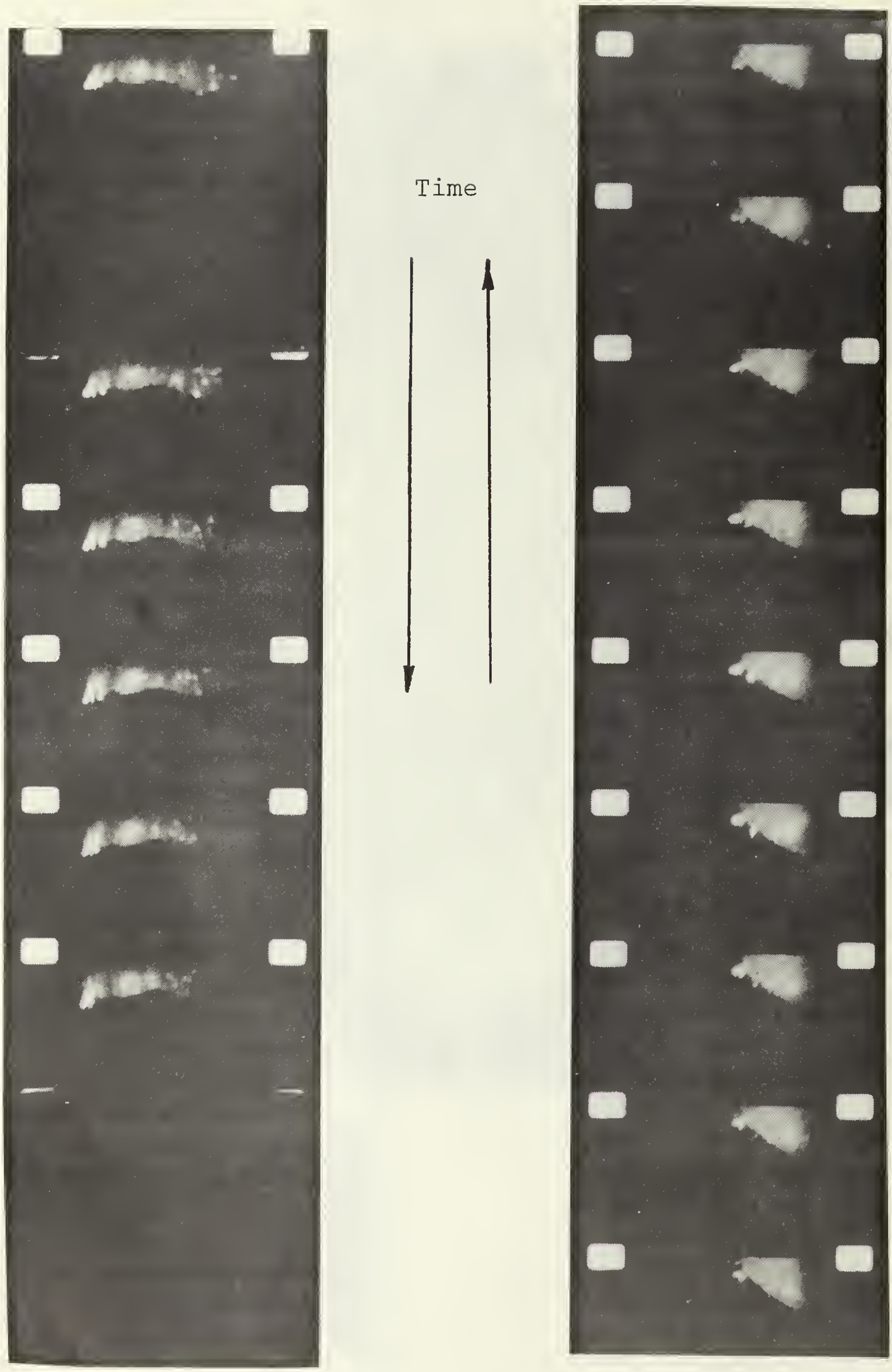


Figure 9. Aluminum Particle Agglomeration, 75 g

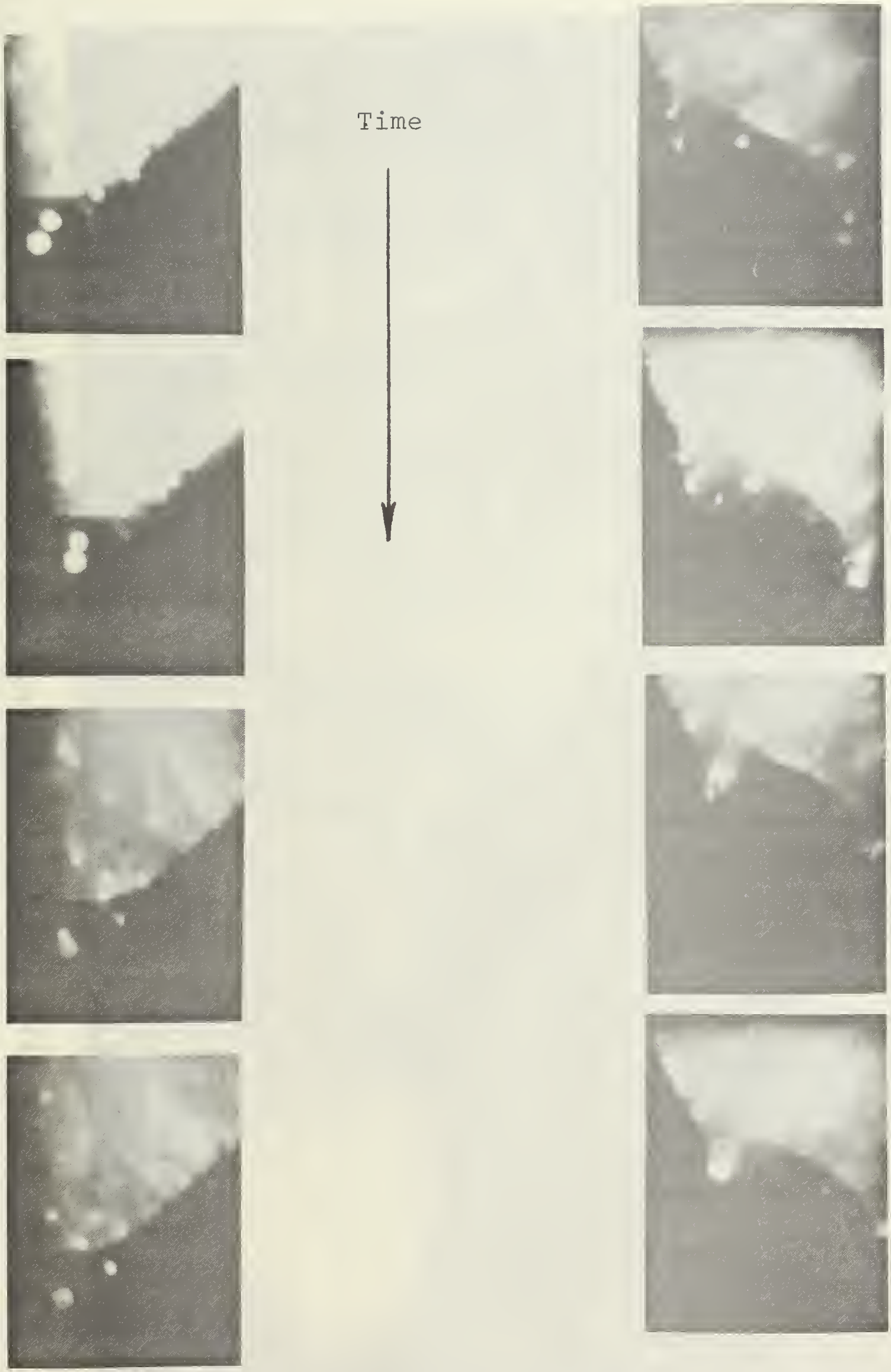


Figure 10. Aluminum Particle Agglomeration, 75 g

Figure 11. Massive Aluminum Agglomeration and Pit Formation, 75 g

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13. ABSTRACT

The influence of an acceleration field on the combustion rate of a composite solid propellant when directed normally and into the burning surface was recorded by high speed cinematography.

One-half to one-inch long propellant strands with 1/4-in by 1/4-in cross sections were burned and photographed at pressures of 200 psi and 500 psi while subjected to normal acceleration fields of 0 g and 75 g.

Aluminized propellants were primarily utilized in this investigation; however, the experimental apparatus and the techniques used proved suitable for general propellant studies.

Propellants burning in acceleration fields of 0 g and 75 g were successfully filmed at frame rates of 4500 pictures per second. The designed magnification factor and the quality of the motion pictures produced provided an optical definition of particle sizes to 100 microns. This film resolution allowed an optical analysis of the acceleration effects on propellant burning rates.

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